Numerical Analysis of River Bank Slope Stability During Rapid Drawdown of Water Level

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Abstract

In the assessment of slopes, factors of safety values remain still the primary indexes for how close or far slope are from failure. The stability of river bank slope during rapid drawdown of river water level was computed using slipping arc stability analysis based on finite element computation according to unsaturated soil shear strength theory in combination with a specific river bank. In the analysis, the dissipating process of pore-water pressure was simulated using unsaturated-unstable seepage theory and the impact of matrix suction on shear strength of soil body was taken into consideration. Traditional limit-equilibrium techniques are the most commonly-used analysis methods to calculate factors of safety for slope and the shear strength reduction (SSR) technique enables the finite element method (FEM) to calculate factors of safety for slopes. The computation results discloses the law of changes in the least safety coefficient with the changes of water level and reflects the impact of different parameters and computation methods on the analyzing results with the stability of slope.

Keywords

River Bank Soil Body; Seepage; Matrix Suction; Slope Stability; FEM; Abaqus; Geo-studio

Introduction

The theory of unsaturated soil mechanics and associated design parameters has been developed for the past few decades. However, due to their complex nature, they have been omitted from routine geotechnical design. Similar to other aspects of geotechnical design, slope stability analysis has been based on the principle of saturated soil mechanics. In recent times, it has become feasible with upgrades to computing technology to evaluate shear strength based unsaturated soil mechanics which optimized the solution using the principle of effective stress. The pore water pressure in the body of river bank usually cannot dissipate in a suitably fast way as rapid drawdown occurs to the water level. In the analysis,

the main classical methods to study stability of slope include limit equilibrium method and shear strength reduction techniques based on finite element method. In the former of which, the stability of slope is determined in consideration of conditions of the balance of static forces of the mass cut by slipping plane with the assumption that the destruction of the slope occurs along a certain slipping plane. While the latter method [Dawson et al, 1999, Griffith and Lane, 1999, Hammah et al, 2004] enables the FEM to calculate factors of safety for slopes. The method enjoys several advantages including the ability to predict stresses and deformations of support elements, such as piles, anchors and geo-textiles, at failure. As well the technique makes it possible to visualize the development of failure mechanisms. In this study, the slope stability method based on finite element analysis was used. Firstly, the analysis on the change of finite element stress of the river bank soil body was conducted, then, the slipping force and anti-slipping force on the slipping plane was analyzed to establish the equilibrium equation based on which the safety coefficient was determined. The slipping plane was transformed to find the slipping plane corresponding to the minimum safety coefficient and thus the most probable slipping plane was obtained. In this study, the finite element analysis software, ABAQUS, and the rock-soil engineering analysis software, GEO/STUDIO (SEEP/W, SLOPE/W, and SIGMA/W) were used for the conduction of finite element analysis and computation of stable seepage and minimum safety coefficient of river bank soil body. SEEP/W, a numerical model that can mathematically simulate the real physical process of water flowing through a particulate medium. SLOPE/W has been designed and developed for the stability analysis of earth structures. SIGMA/W can be used to compute stress-deformation with or without the changes in pore-water pressures that arise from stress state changes.

Principal Theory for the Analysis of Stability of River Bank Slope

Mathematical Models for the Saturated Unsaturated Seepage

The basic equation for the saturated-unsaturated seepage can be obtained according to law of conservation of mass for the liquid phase of non-saturated soil.

$$\frac{\partial \theta_w}{\partial t} = \left[\frac{k_{wij}}{\rho_w g} (P_{w,j} - \rho_w b_j) \right] \qquad (1)$$

Where k_{wij} refers to seepage coefficient: ρ_w refers to the density of water: b_j refers to force per unit volume: θ_w refers to water content in volume: g indicates gravitational acceleration: and $P_{w,j}$ is derivation along the y-axis. The relationship between the saturation and the matrix suction obtained by room tests can be defined as: $C_s = n \frac{\partial \theta_w}{\partial P_w}$, equation (1) can be modified into torque-vector pattern.

$$\nabla^T \bar{k} \rho_w b + C_s P_w - \nabla^T \bar{k} \square P_w = 0 \qquad (2)$$

Where, $\bar{k} = \frac{k}{\rho_w g}$; $\nabla^T = \left\{ \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right\}$

The boundary condition must also be introduced when finite element solution is used:

$$\rho_w = \square_{w'} [\Gamma_p \text{ Boundary}] \qquad (3)$$

$$\left[\bar{k} \rho_w b - \bar{k} P_w \right]^T n = \tilde{q} \ ,[\Gamma_q \text{ Boundary}] \qquad (4)$$

The continuous equation (1) can also modified into the form with the overall water pressure ϕ_w being variable according to the definition of ϕ_w, then

$$\phi_w = \frac{P_w}{\rho_w g} + y \qquad (5)$$

Where y is the positional water pressure and put equation (5) to equation (1), and assume that y-axis is the same as the gravitational acceleration in direction, then, the following equation is obtained.

$$C_s \rho_w g \frac{\partial \phi_w}{\partial t} = [k_{wij} \phi_{w,j}], i \qquad (6)$$

The corresponding equation with finite element method can also be obtained according to the equation above. Eventually, the non-linear iterate technique can be used, and the distribution of the pore water pressure (or saturation magnitude) and the location of the phreatic line at each different time point is obtained.

Shear Strength Theory for Unsaturated Soil

The shearing strength of soil body refers to its limit capacity against destruction from shearing, which can have significant impact on the stability of slope. The traditional equation such as the Mohr-Coulomb destruction principle are not suitable for the expression of shearing strength unsaturated soil due to the existent absorbability of its matrix which leads to its shearing strength extremely complex. As a result, it is crucially important to determine the equation of unsaturated soil when doing analysis of the stability of the slope. At present, the two-parameter models formulated by Fredlund have been widely accepted by experts in rock- soil study field.

$$\tau' = c' + (\sigma_f - u_a)_f \tan\phi' + (u_a - u_w)\tan\phi^b \qquad (7)$$

Where, c' is the effective cohesion; $(\sigma_f - u_a)_f$ is the effective normal stress; ϕ' is the effective angle of the internal friction; $(u_a - u_w)$ is the matrix suction; ϕ^b is an angle defining the increase in shear strength for an increase in suction.

The Limit Equilibrium Approach

Limit equilibrium analyses solve the problem from the assumption of force and/or moment equilibrium. Duncan (1996) states that the factor of safety, F, is defined as the ratio of the shear strength of soil to the shear stress required for equilibrium. At the onset of failure the shear strength along the slip surface is assumed to be fully mobilized and the factor of safety is constant along the length of the entire surface. The factor of safety from the Spencer method will be used for the purposes of this research as it is prone to the least amount of errors and is most suitable to the problem.

Finite Element Method

Using the finite element method (FEM) of analysis is a numerical solution technique which requires initial conditions, boundary conditions and the stress–strain properties of the soil. Tan &Sarma (2008) reported that the FEM calculates the stress and deformation of the soil and interprets a slip surface from the regions of high strain. The FEM uses the strength reduction technique by factoring the model parameters c and φ. The strength reduction factor is gradually increased until failure of the slope occurs, when the algorithm cannot find a stress redistribution to satisfy the global equilibrium and Mohr-Coulomb criterion, at this point the factor of safety is equal to the strength reduction factor. In the analysis of the stability of slope with finite element analysis method, the finite element computation is used mainly to obtain the stress field, to pursue the normal stress and tangent stress on the

slipping plane, to determine the safety coefficient according to the equilibrium of forces and then to find the slipping plane at the minimum stable safety coefficient after the alteration of slipping plane. Firstly, the body of the river bank is computed with finite element method to obtain the sub-quantity of the stress per unit, then, the normal and tangent stress on the slipping plane is computed based on the assumption of the slipping plane. Let the soil body on the slipping plane be disassociated body, then, the torque equilibrium equation is established;

$$F_s \int \tau dA = \int S dA \qquad (8)$$

Where, F_s is the overall stability safety coefficient of side slope, s is the anti-slipping force on the slipping plane; τ is the slipping force on slipping plane. Under the condition of unsaturated soil body, the anti-slipping force can be expressed as the following:

$$S = c' + (\sigma_n - u_a)_f \tan\phi' + (u_a - u_w)\tan\phi^b \qquad (9)$$

The above is only one risky slipping plane and its corresponding safety coefficient. Then multiple slipping plane are assumed, and the computation above it is repeated to find the location of the slipping plane of the most risky, and eventually, the minimum safety coefficient, $F_{s\min}$, is determined.

Numerical Result and Discussion

Geological Parameters of River Bank in Twante Canal

Twante canal connects the Irrawaddy River and the Yangon River with the length of 22 miles and a heavily used short cut between Yangon and Irrawaddy Division of Myanmar. The study location is Latpangon bank of Twante canal, 3.5 miles far away from Yangon River, and its bank soil is non-homogeneous soil. From ground level to the depth 60 feet of the banks is composed of 9 different soil layers.

Twante canal suffers semi-diurnal tide, rising up and falling down of water level happens twice in a day. Since the rapid drawdown of water level in the canal greatly effects the slope stability of river banks. In the study, the effect of rapid drawdown of water level on slope stability is analyzed. The difference of design water level from high water level to low water level is taken as 18 feet and its duration is 6.5 hours from water level record of DWIR sub-office of Latpangon station (3.5 miles station) in 2012.
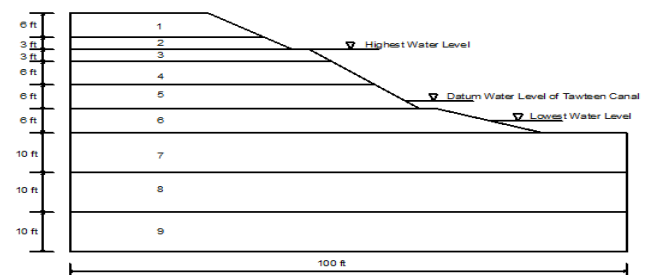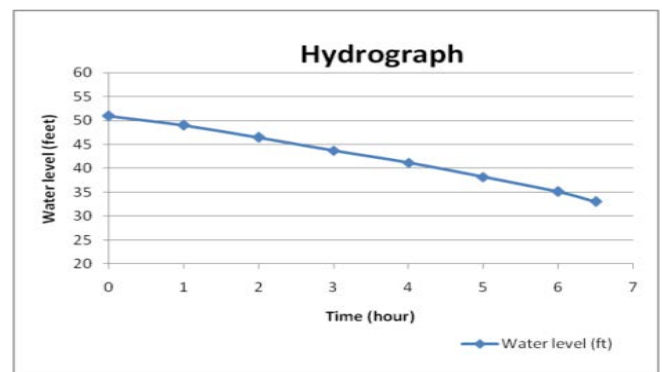

FIG. 1 GEOMETRY OF LATPANGON BANK

FIG. 2 WATER LEVEL DRAWDOWN HYDROGRAPH

TABLE 1 GEOLOGICAL SOIL PARAMETERS OF LATPANGON BANK IN TWANTE CANAL (3.5 Miles)

No.	Soil Layer	Water Content (%)	Cohesion c (lb/ft²)	Friction Angle, φ (degree)	Density of soil γ (lb/ft³)	Modulus of soil, E (lb/ft²)	Poisson Ratio (υ)	Permeability Coefficient, k (ft/sec)
1	Brownish Gray Clayey Silt, trace Sand and trace Gravel	37.29	504.00	1° 00'	71.69	3.133 x10⁵	0.30	3.28 x 10⁻⁴
2	Dark Gray Clayey Silt, trace Sand and trace Gravel	42.54	345.60	1° 30'	64.57	5.013 x 10⁵	0.32	1.17 x 10⁻⁴
3	Gray Clayey Silt ,trace Sand	27.28	864.00	5° 00'	89.89	6.893 x 10⁵	0.33	1.89 x 10⁻⁵
4	Brownish Gray Clay Silt, some Silt	42.67	316.80	3° 00'	101.69	6.266 x 10⁵	0.34	1.25 x 10⁻⁶
5	Dark Gray Clayey Silt, some Silt	37.24	388.80	1° 00'	104.15	8.146 x 10⁵	0.40	4.33 x 10⁻⁷
6	Dark Gray Sand and Silt, some Clay	38.92	246.90	1° 30'	99.63	9.399 x 10⁵	0.35	1.39 x 10⁻⁷
7	Dark Gray Clayey Silt, some Sand	36.17	532.80	1° 00'	102.73	15.247 x 10⁵	0.38	2.14 x 10⁻⁶
8	Gray Sand, trace Silt	22.31	164.00	15 00'	110.41	16.917 x 10⁵	0.40	8.2 x 10⁻⁴
9	Gray Sand and Silt, some Clay	24.72	328.00	10° 00'	107.17	15.664 x10⁵	0.33	2.47 x 10⁻⁴

Analysis of Seepage Drawdown Line during River Water Level drawdown

In this study, the initial boundary condition of the water level is 51 feet and transient boundary condition of water level is 33 feet and the duration is 6.5 hours. Each finite element size is one foot in all dimensions. Since the duration of water level drawdown is short, the water level will be rising up after transient condition and the high permeability of the soil layers, the phreatic lines don't change significantly. During the process of drawdown of the river water level to different elevations, unstable seepage was formed in the soil body, the pore-water pressures at different points continuously changed, and the unsaturated region continuously reflected that the location of phreatic line intermittently dropped and tended to be stable with the elongation of the time.
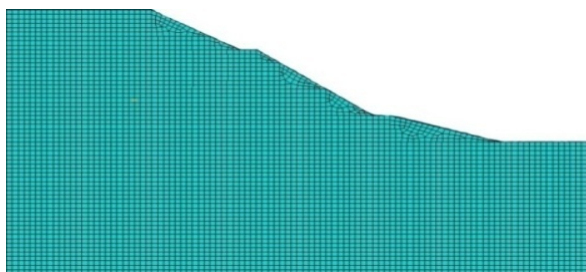

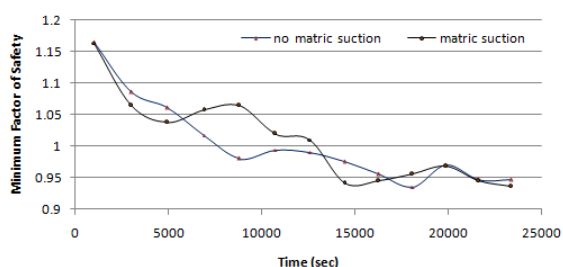
FIG. 3 FINITE ELEMENT GRIDS IN ABAQUS MODEL

FIG. 4 CHANGE OF F_{smin} WITH WATER LEVEL DRAWDOWN TIME

Effect of Drawdown of Water Level on the Minimum Stability Safety Coefficient

The relationship among the minimum stability safety coefficient, F_{smin}, obtained by computation and the time, t, was shown in Fig. 4, when the stability of the slope was analyzed in relation to seepage field at different time points. During the instantaneous period of drawdown of water level, the effect of the matrix suction on F_{smin} was not significant due to the untimely excluding of the pore-water pressure; in addition, the safety coefficient of the slope of the river bank was minimal at the rapid drawdown of the water level. The safety coefficient tended to become larger with the exclusion of the excess pore-water pressure with the

relapse of the time. Therefore, the rapid drawdown period is the most unsafe of all for the slope of the river bank when rapid drawdown of water level occurs.
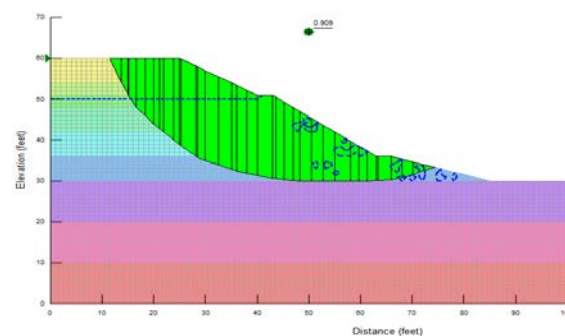

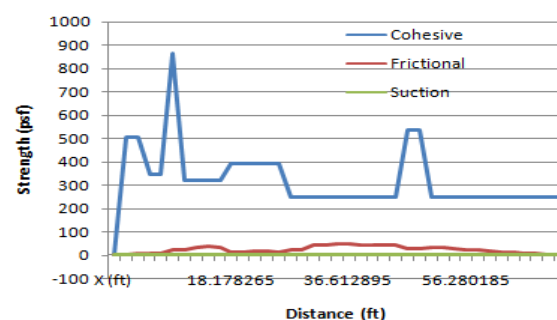FIG. 5 F_{smin} FROM FINITE ELEMENT ANALYSIS

FIG. 6 ANTI-SHEARING FORCE OF SLIPPING ARC

Effect of the Matrix Suction on the Minimum Stability Safety Coefficient

The stability of the slope of the river bank was computed when the occurrence of rapid drawdown of water level with and without considering the matrix suction respectively. The temporal process line for the minimum safety coefficient of the slope of the river bank was shown in Fig. 4, from which it can be known that the slipping plane is mainly located in the saturated region in the initial period of drawdown of the water level when the water level of the river is comparatively high. As a result, the safety coefficients obtained by the computation with the two methods are not significantly different from each other. With drawdown of the water level, the excess pore water pressure was decreased, the unsaturated region was enlarged, the shearing strength of unsaturated soil was remarkably increased by the matrix suction, and thus the safety coefficient obtained by the computation considering the matrix suction was significantly larger than that obtained by the computation considering the matrix suction. The increment of the matrix suction elevates the shearing capacity of the soil with the increasing difference of the two coefficients. Therefore, the impact of the matrix suction in unsaturated region on increasing shear strength of the soil must be taken

into consideration when the water level is low. Fig. 6 illustrates the distribution curve of shear strength of slipping arc under the operating mode considering matrix suction, showing that there are actually three strength components and matrix suction can significantly enhance anti-slipping strength.

Computational Result Analysis between Limit Equilibrium Method and Shear Strength Reduction Technique

Bishop method, Ordinary method, Spencer method, Janbu method and finite element method have been used respectively to compute the same slipping arc in order to confirm the reasonability of the present methods. The computed results are shown in table 2.

TABLE 2 COMPUTATION RESULT OF F_{smin}

Analysis method	Operation mode	F_{smin}
Limit equilibrium analysis method	Bishop method	0.961
	Ordinary method	1.036
	Spencer method	0.936
	Janbu method	0.993
Shear strength reduction technique	Finite element method	0.909

Conclusions

The use of the finite element method yields more detailed information on the stress state in the soil compared to conventional limit equilibrium methods. This information can assists engineers in the design of slopes and slope retaining structures. The results of the analysis showed that the analysis of the stability of the slope of the river bank based on finite element stress-strain analysis can reflect the real stress state and the reasonable determination of the distribution of the pore-water pressure and saturation in rock-soil body is crucial for the results of computation. The method overcomes the disadvantages of limit equilibrium method and is suitable for any complex boundary conditions. The results of computation showed that rapid drawdown of river water level most easily leads to the slipping of the slope of the river bank, and the stability of the slope of the river bank gradually increases with the dissipation of the excess pore-water pressure. The contribution of the matrix suction to shearing strength increases with the enlargement of unsaturated soil region, which has remarkable action on raising the stability of the slope of the river bank. Therefore, the monitoring of the river bank soil body should be intensified during rapid drawdown of river water level so as to avoid the occurrence of slipping of the slope of the river bank.

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